An extended Higgs sector for neutrino mass, dark matter and baryon asymmetry

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In this talk [1], we discuss a TeV scale model which would explain neutrino oscillation, dark matter, and baryon asymmetry of the Universe simultaneously by the dynamics of the extended Higgs sector and TeV-scale right-handed neutrinos. By the imposed exact Z_2 symmetry, tiny neutrino masses are generated at the three loop level, and the stability of the dark matter candidate, an additional singlet scalar field, is guaranteed. The extra Higgs doublet is introduced not only for neutrino masses but also for successful electroweak baryogenesis. The model provides various discriminative predictions in Higgs phenomenology, which can be tested at the Large Hadron Collider and the International Linear Collider.

1 Introduction

Although the Standard Model (SM) has been successful, a new model beyond the SM must be considered to understand the phenomena such as tiny neutrino masses and their mixing [2], the nature of dark matter (DM) [3] and baryon asymmetry of the Universe [4]. It has been clarified that they are all beyond the scope of the SM.

We discuss a model which would explain these problems simultaneously by an extended Higgs sector with TeV-scale right-handed (RH) neutrinos [5]. Tiny neutrino masses are generated at the three loop level due to an exact discrete symmetry, by which tree-level Yukawa couplings of neutrinos are prohibited. The lightest neutral odd state under the discrete symmetry is a candidate of DM. Baryon number can also be generated at the electroweak phase transition (EWPT) by additional CP violating phases in the Higgs sector [6]. In this framework, a successful model can be made without contradiction of the current data.

Original idea of generating tiny neutrino masses via the radiative effect has been proposed by Zee [7]. The extension with a TeV-scale RH neutrino has been discussed in Ref. [8], where neutrino masses are generated at the three-loop level due to the exact Z_2 parity, and the Z_2-odd RH neutrino is a candidate of DM. This has been extended with two RH neutrinos to describe the neutrino data [9]. Several models with adding baryogenesis have been considered in Ref. [10]. The following advantages would be in the present model: (a) all mass scales are at most at the TeV scale without large hierarchy, (b) physics for generating neutrino masses is connected with that for DM and baryogenesis, (c) the model parameters are strongly constrained by the current data, so that the model provides discriminative predictions which can be tested at future experiments.

In the following, we first explain the basic properties of the model, and discuss its phenomenology at the International Linear Collider (ILC).

	Q^i	u_R^i	d_R^i	L^i	e_R^i	Φ_1	Φ_2	$S^\pm$	η	N_R^α
Z_2 (exact)	+	+	+	+	+	+	+	$-$	$-$	$-$
$\tilde{Z}_2$ (softly broken)	+	$-$	$-$	+	+	+	$-$	+	$-$	+

Table 1: Particle properties under the discrete symmetries.

2 Model

We introduce two scalar isospin doublets with hypercharge $1/2$ (Φ_1 and Φ_2), charged singlet fields ($S^\pm$), a real scalar singlet (η) and two generation isospin-singlet RH neutrinos (N_R^α with $\alpha = 1, 2$). We impose an exact Z_2 symmetry to generate tiny neutrino masses at the three-loop level, which we refer as Z_2. We assign Z_2-odd charge to $S^\pm$, η and N_R^α, while ordinary gauge fields, quarks and leptons and Higgs doublets are Z_2 even. In order to avoid the flavor changing neutral current in a natural way, we impose another (softly-broken) discrete symmetry ($\tilde{Z}_2$) [11]. We assign $\tilde{Z}_2$ charges such that only Φ_1 couples to leptons whereas Φ_2 does to quarks;

$$\mathcal{L}_Y = -y_{e_i} \overline{L}^i \Phi_1 e_R^i - y_{u_i} \overline{Q}^i \tilde{\Phi}_2 u_R^i - y_{d_i} \overline{Q}^i \Phi_2 d_R^i + \text{h.c.}, \qquad (1)$$

where Q^i (L^i) is the ordinary i-th generation left-handed (LH) quark (lepton) doublet, and u_R^i and d_R^i (e_R^i) are RH-singlet up- and down-type quarks (charged leptons), respectively. We summarize the particle properties under Z_2 and $\tilde{Z}_2$ in Table 1.

The Yukawa coupling in Eq. (1) is different from that in the minimal supersymmetric SM (MSSM) [12]. In addition to the usual potential of the two Higgs doublet model (THDM) with the $\tilde{Z}_2$ parity and that of the Z_2-odd scalars, we have the interaction terms between Z_2-even and -odd scalars:

$$\mathcal{L}_{int} = -\sum_{a=1}^{2} \left(\rho_a |\Phi_a|^2 |S|^2 + \sigma_a |\Phi_a|^2 \frac{\eta^2}{2} \right) - \sum_{a,b=1}^{2} \left\{ \kappa \, \epsilon_{ab} (\Phi_a^c)^\dagger \Phi_b S^- \eta + \text{h.c.} \right\}, \qquad (2)$$

where ϵ_{ab} is the anti-symmetric tensor with $\epsilon_{12} = 1$. The mass term and the interaction for N_R^α are given by

$$\mathcal{L}_{Y_N} = \sum_{\alpha=1}^{2} \left\{ \frac{1}{2} m_{N_R^\alpha} \overline{N_R^{\alpha c}} N_R^\alpha - h_i^\alpha \overline{(e_R^i)^c} N_R^\alpha S^- + \text{h.c.} \right\}. \qquad (3)$$

Although the CP violating phase in the Lagrangian is crucial for successful baryogenesis at the EWPT [6], it does not much affect the following discussions. Thus, we neglect it for simplicity. We later give a comment on the case with the non-zero CP-violating phase.

As Z_2 is exact, the even and odd fields cannot mix. Mass matrices for the Z_2 even scalars are diagonalized as in the usual THDM by the mixing angles α and β, where α diagonalizes the CP-even states, and $\tan \beta = \langle \Phi_2^0 \rangle / \langle \Phi_1^0 \rangle$ [12]. The Z_2 even physical states are two CP-even (h and H), a CP-odd (A) and charged ($H^\pm$) states. We here define h and H such that h is always the SM-like Higgs boson when $\sin(\beta - \alpha) = 1$.

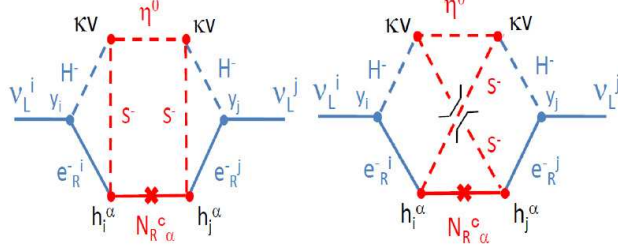Figure 1: The diagrams for generating tiny neutrino masses.

Set	h_e^1	h_e^2	h_μ^1	h_μ^2	h_τ^1	h_τ^2	$B(\mu\to e\gamma)$
A	2.0	2.0	-0.019	0.042	-0.0025	0.0012	6.9×10^{-12}
B	2.2	2.2	0.0085	0.038	-0.0012	0.0021	6.1×10^{-12}

Table 2: Values of h_i^α for $m_{H^\pm}(m_{S^\pm}) = 100(400)$ GeV, $m_\eta = 50$ GeV, $m_{N_R^1} = m_{N_R^2} = 3.0$ TeV for the normal hierarchy. For Set A (B), $\kappa\tan\beta = 28(32)$ and $U_{e3} = 0(0.18)$. Predictions on the branching ratio of $\mu \to e\gamma$ are also shown.

3   Neutrino Mass, Dark Matter, and Strongly 1st-Order Phase Transition

The LH neutrino mass matrix M_{ij} is generated by the three-loop diagrams in Fig. 1. The absence of lower order loop contributions is guaranteed by Z_2. $H^\pm$ and e_R^i play a crucial role to connect LH neutrinos with the one-loop sub-diagram by the Z_2-odd states. We obtain

$$M_{ij} = \sum_{\alpha=1}^{2} C_{ij}^\alpha F(m_{H^\pm}, m_{S^\pm}, m_{N_R^\alpha}, m_\eta), \tag{4}$$

where $C_{ij}^\alpha = 4\kappa^2\tan^2\beta(y_{e_i}^{\mathrm{SM}}h_i^\alpha)(y_{e_j}^{\mathrm{SM}}h_j^\alpha)$ with $y_{e_i}^{\mathrm{SM}} = \sqrt{2}m_{e_i}/v$ and $v \simeq 246$ GeV. The factor of the three-loop integral function $F(m_{H^\pm}, m_{S^\pm}, m_{N_R}, m_\eta)$ includes the suppression factor of $1/(16\pi^2)^3$, whose typical size is $\mathcal{O}(10^4)$eV. Magnitudes of $\kappa\tan\beta$ as well as F determine the universal scale of M_{ij}, whereas variation of h_i^α ($i = e$, μ, τ) reproduces the mixing pattern indicated by the neutrino data [2].

Under the *natural* requirement $h_e^\alpha \sim \mathcal{O}(1)$, and taking the $\mu \to e\gamma$ search results into account [13], we find that $m_{N_R^\alpha} \sim \mathcal{O}(1)$ TeV, $m_{H^\pm} \lesssim \mathcal{O}(100)$ GeV, $\kappa\tan\beta \gtrsim \mathcal{O}(10)$, and $m_{S^\pm}$ being several times 100 GeV. On the other hand, the LEP direct search results indicate $m_{H^\pm}$ (and $m_{S^\pm}$) $\gtrsim 100$ GeV [2]. In addition, with the LEP precision measurement for the ρ parameter, possible values uniquely turn out to be $m_{H^\pm} \simeq m_H$ (or m_A) $\simeq 100$ GeV for $\sin(\beta - \alpha) \simeq 1$. Thanks to the Yukawa coupling in Eq. (1), such a light $H^\pm$ is not excluded by the $b \to s\gamma$ data [14]. Since we cannot avoid to include the hierarchy among y_i^{SM}, we only require $h_i^\alpha y_i \sim \mathcal{O}(y_e) \sim 10^{-5}$ for values of h_i^α. Our model turns out to prefer the normal hierarchy scenario. Several sets for h_i^α are shown in Table 2 with the predictions on the branching ratio of $\mu \to e\gamma$ assuming the normal hierarchy.
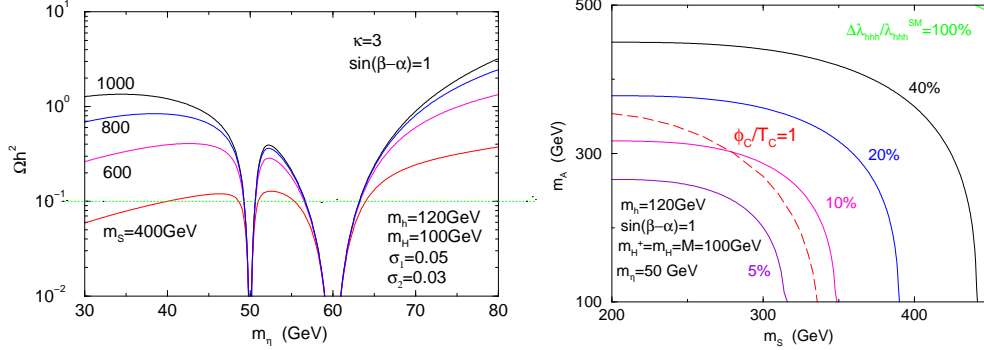
Figure 2: [Left figure] The relic abundance of η. [Right figure] The region of strong first order EWPT. Deviations from the SM value in the hhh coupling are also shown.

The lightest Z_2-odd particle is stable and can be a candidate of DM if it is neutral. In our model, N_R^α must be heavy, so that the DM candidate is identified as η. When η is lighter than the W boson, η dominantly annihilates into $b\bar{b}$ and $\tau^+\tau^-$ via tree-level s-channel Higgs (h and H) exchange diagrams, and into $\gamma\gamma$ via one-loop diagrams. From their summed thermal averaged annihilation rate $\langle\sigma v\rangle$, the relic mass density $\Omega_\eta h^2$ is evaluated. Fig. 2(Left) shows $\Omega_\eta h^2$ as a function of m_η. Strong annihilation can be seen near 50 GeV $\simeq m_H/2$ (60 GeV $\simeq m_h/2$) due to the resonance of H (h) mediation. The data ($\Omega_{\rm DM} h^2 \simeq 0.11$ [3]) indicate that m_η is around 40-65 GeV.

The model satisfies the necessary conditions for baryogenesis [4]. Especially, departure from thermal equilibrium can be realized by the strong first order EWPT. The free energy is given at a high temperature T by

$$V_{eff}[\varphi, T] = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + ..., \qquad (5)$$

where φ is the order parameter. A large value of the coefficient E is crucial for the strong first order EWPT with keeping $m_h \lesssim 120$ GeV. For sufficient sphaleron decoupling in the broken phase, it is required that [15]

$$\frac{\varphi_c}{T_c} \left(\simeq \frac{2E}{\lambda_{T_c}}\right) \gtrsim 1, \qquad (6)$$

where φ_c ($\neq 0$) and T_c are the critical values of φ and T at the EWPT. In Fig. 2(Right), the allowed region under the condition of Eq. (6) is shown. The condition is satisfied when $m_{S^\pm} \gtrsim 350$ GeV for $m_A \gtrsim 100$ GeV, $m_h \simeq 120$ GeV, $m_H \simeq m_{H^\pm}(\simeq M) \simeq 100$ GeV and $\sin(\beta - \alpha) \simeq 1$.

4   Phenomenology

A successful scenario which can simultaneously solve the above three issues under the data [2, 13, 14] would be

$$\begin{aligned} &\sin(\beta - \alpha) \simeq 1, \qquad \kappa\tan\beta \simeq 30, \qquad m_h = 120\text{GeV}, \ \ m_H \simeq m_{H^\pm} \simeq \mathcal{O}(100)\text{GeV}, \\ &m_A \gtrsim \mathcal{O}(100)\text{GeV}, \ \ m_{S^\pm} \sim 400\text{GeV}, \ \ m_\eta \lesssim m_W, \qquad m_{N_R^1} \simeq m_{N_R^2} \simeq 3\text{TeV}. \end{aligned} \qquad (7)$$

This is realized without assuming unnatural hierarchy among the couplings. All the masses are between $\mathcal{O}(100)$ GeV and $\mathcal{O}(1)$ TeV. The discriminative properties of this scenario are in order:

(I) h is the SM-like Higgs boson, but decays into $\eta\eta$ when $m_\eta < m_h/2$. The branching ratio is about 30% for $m_\eta \simeq 43$ GeV and $\tan\beta = 10$: see Fig. 3. This is related to the DM abundance, so that our DM scenario is testable at the CERN Large Hadron Collider (LHC) and the ILC by searching the missing decay of h. Furthermore, η is potentially detectable by direct DM searches [16], because η can scatter with nuclei via the scalar exchange [17].

(II) For successful baryogenesis, the hhh coupling has to deviate from the SM value by more than 10-20 % [18] (see Fig. 2), which can be tested at the ILC [19].

(III) H (or A) can predominantly decay into $\tau^+\tau^-$ instead of $b\bar{b}$ for $\tan\beta \gtrsim 2$. The scenario with light $H^\pm$ and H (or A) can be directly tested at the LHC via $pp \to W^* \to HH^\pm$ and $AH^\pm$ [20], and also $pp \to HA$. Their signals are four lepton states $\ell^-\ell^+\tau^\pm\nu$ and $\ell^-\ell^+\tau^+\tau^-$, where ℓ represents μ and τ [21].

(IV) At the ILC, the process $e^+e^- \to HA$ would be useful to discriminate the model from the other new physics candidates. In Fig. 4, the production rate of the $e^+e^- \to HA$ is shown for $m_A = m_H$. In our model, we have $B(H(A) \to \tau^+\tau^-) \simeq 100$ % and $B(H(A) \to \mu^+\mu^-) \simeq 0.3$ % for $m_A = m_H = 130$ GeV, $\sin(\beta - \alpha) = 1$ and $\tan\beta = 10$. For $\sqrt{s} = 500$ GeV, about 17,000, (110) of the $\tau^+\tau^-\tau^+\tau^-$ ($\mu^+\mu^-\tau^+\tau^-$) events are then produced from the signal [21], while about 60 (0) events are in the MSSM for the similar parameter set. The main back ground comes from ZZ production (about 400 fb), which is expected to be easily reduced by appropriate kinematic cuts.

(V) $S^\pm$ can be produced in pair at the LHC and the ILC [22], and decay into $\tau^\pm\nu\eta$. The signal would be a hard hadron pair with a large missing energy [23].

(VI) The couplings h_i^α cause lepton flavor violation such as $\mu \to e\gamma$ which would provide information on $m_{N_R^\alpha}$ at future experiments.

Finally, we comment on the case with the CP violating phases. Our model includes the THDM, so that the same discussion can be applied in evaluation of baryon number at the EWPT [6]. The mass spectrum would be changed to some extent, but most of the features
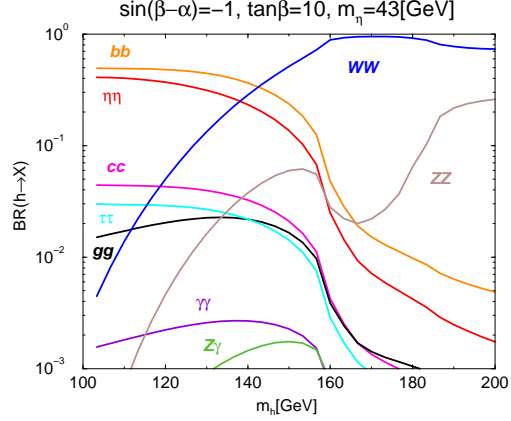

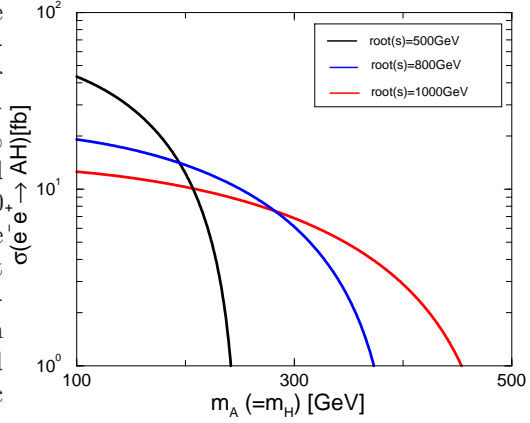Figure 3: The decay branching rations of the SM-like Higgs boson h.

Figure 4: The production cross section of $e^+e^- \to HA$.

discussed above should be conserved with a little modification.

5 Summary

In this talk, we have discussed the model with the extended Higgs sector and TeV-scale RH neutrinos, which would explain neutrino mass and mixing, DM and baryon asymmetry by the TeV scale physics. It gives specific predictions on the collider phenomenology. In particular, the predictions on the Higgs physics are completely different from those in the MSSM, so that the model can be distinguished at the LHC and also at the ILC.

6 Acknowledgments

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